Magnetotelluric Exploration at Tendaho High Temperature Geothermal Field in North East Ethiopia

Yohannes Lemma[1], Ulrich Kalberkamp[2], Fisum Abera[1], Kassahun Dendere[1], and Yiheyis Kebede[1]

[1]Geological Survey of Ethiopia, Addis Ababa, Ethiopia
[2]Geological Survey of Germany, GEOTHERM Programme
Hannover, Germany
yohanesle207@gmail.com

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ABSTRACT

Tendaho is one of the high temperature geothermal areas in Afar depression in north east Ethiopia. A total of 85 MT sites were acquired from Tendaho high temperature field. The main objective of this study is to understand the deep geothermal reservoir not reached by vertical electrical sounding. 2D inversion of MT data along seven profiles was performed in Dubti, Ayrobera and Kurub areas. The 2D inversion of MT data from Tendaho high temperature field revealed three main resistivity structures down to a depth of 10 km: low resistivity surface layer underlain by a resistive layer followed by good conducting structure. The low resistivity surface layer can be interpreted as sediments, lateral flow of geothermal fluids or Zeolite-clay alteration zone. Below the conductive layer, high resistivity is observed, which can be correlated to Afar stratoid basalts or epidote alteration zone .The high resistivity structure can also be associated with the deep reservoir of the geothermal system. The deep highly conductive body is presumably associated with the heat source of the geothermal system. The possible fracture zone inferred in the Afar stratoid basalts may give high temperature and high permeability. The 2D resistivity elevation slices showed possible upflow zone south east of the exploratory wells drilled in Dubti area.

1. Introduction

A magnetotelluric (MT) survey was conducted at Tendaho high temperature geothermal field in 2010/11 as a joint collaboration project between the Ministry of Mines of Ethiopia (MME), through Geological Survey of Ethiopia (GSE), and the German Federal Institute of Geosciences and Natural Resources (BGR) - GEOTHERM programme.

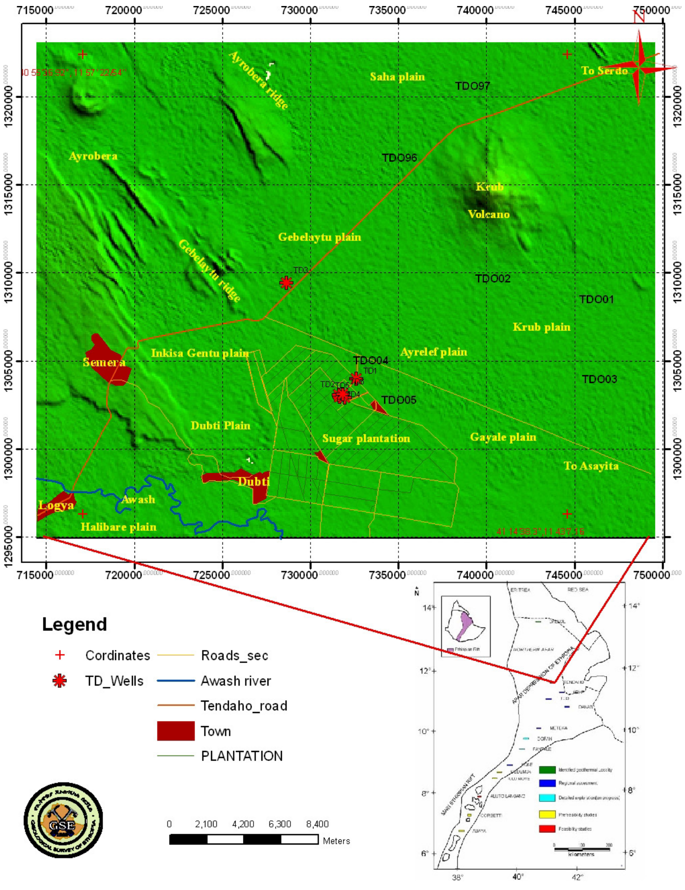

Figure 1. Location Map of Tendaho Geothermal Field.

The Tendaho geothermal field is located in the central part of the Afar Depression about 600 km from Addis Ababa in the north-eastern part of Ethiopia (Figure 1). The approximate geographical location of the MT study area as a whole is 40° 55'36.92" E and 41° 44'38.3" longitude and 11° 57'22.574"N and 11° 43'7.16" latitude shown in Figure 1.

2. MT Data Acquisition and Processing

A 5-channel MT data acquisition system (MTU-5A) from Phoenix Geophysics Ltd was used to record the MT data. The induction coil MTC-50 used covers frequency ranges from 0.0001 Hz up to 400 Hz. The electrodes used are composed of PbCl2 solution in a ceramic container that is designed to ensure a good contact between the outside wires and the soil. The dipole length between the electrodes used was 100 m; with some exception of 50 m. A total of 85 MT soundings were collected in Tendaho geothermal field along seven profiles (Figure 2). The direction of the seven profiles was chosen approximately perpendicular to the known geologic strike direction of the Tendaho graben. The station spacing on the profiles is mostly about 1 Km.

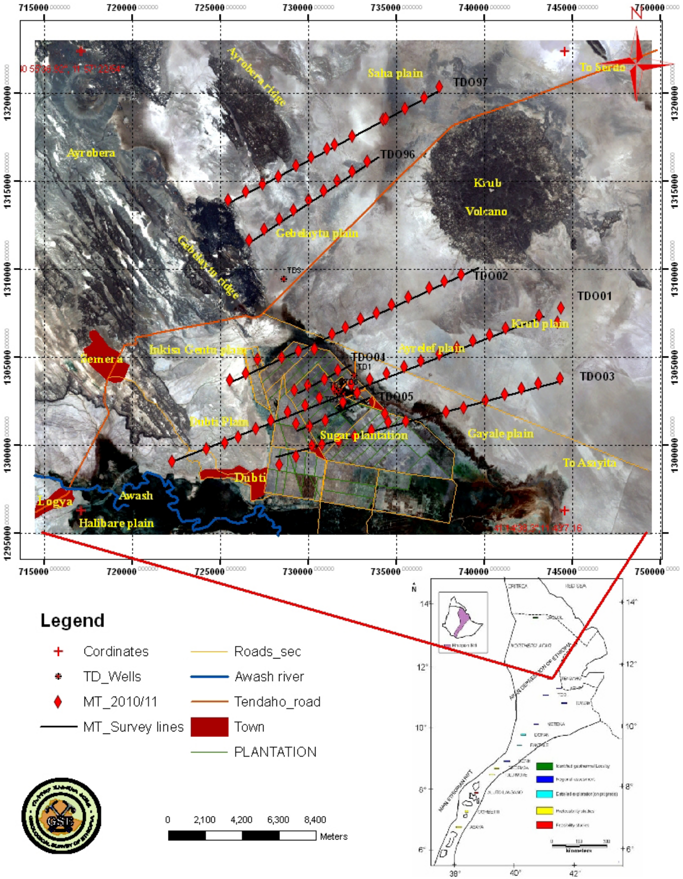

Figure 2. Elevation map of Tendaho area showing MT profiles.

The impedance and geomagnetic transfer functions were obtained using the robust processing program SSMT2000 provided by Phoenix Geophysics-Canada (Phoenix Geophysics, 2005). To analyze dimensionality of the MT data, impedance polar diagrams was used. A typical example of impedance polar diagram from the 85 MT sites at a frequency of 0.01 Hz is shown in Figure 3. The polar diagrams were plotted from measured data.

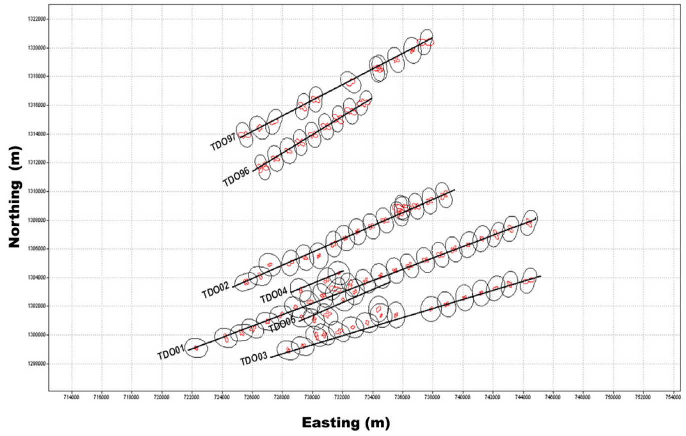

Figure 3. Impedance Polarization map for MT sites. |Zxx| =red colour and |Zxy|= black colour in the polar diagram.

The dimensionality information from the polar diagrams on Figures 3 show mostly 2D resistivity structure at the frequencies and soundings considered. The geoelectric strike direction was analyzed using the program strike by McNeice and Jones (2001). The multi-site, multi-period analysis of the regional strike direction resulted in N25°W dominant strike direction. Therefore, 2D inversion of the MT data was carried out.

Prior to 2D inversion, the MT data were rotated to -25°. The program WinGLink developed by Randy Mackie was used for the 2D inversion. The 2D inversion of the MT data was done using a smooth model inversion routine. This routine finds regularized solution to the 2D inverse problem for MT data using the method of nonlinear conjugate gradients (Rodi and Mackie, 2001).

3. Results From 2D Inversion

2D MT cross section TDO01, (Figures 2 and 4), runs from Hali Bare Plain in SW and ends Kurub plain in the NE with a total distance of about 24 km. A good conducting (≤ 7 Ωm) surface layer which is about 1 km thick, underlain by high resistivity layer (≥ 7 Ωm) (Figure 4). Below the resistive layer, low resistivity (≤ 7 Ωm) is observed. The good conducting surface layer can be interpreted as sediments, lateral flow of geothermal fluid or zeolite/smectite alteration zone. The resistive second layer can be associated with Afar stratoid series basalts or chlorite-epidote alteration zone. The conductive body (< 7 Ω m) at depth of about 4.5 km is presumably associated with the heat source of

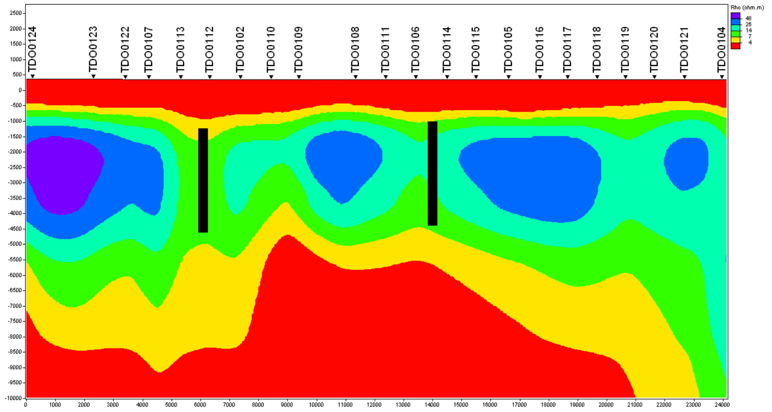

Figure 4. 2D MT cross section TDO01.

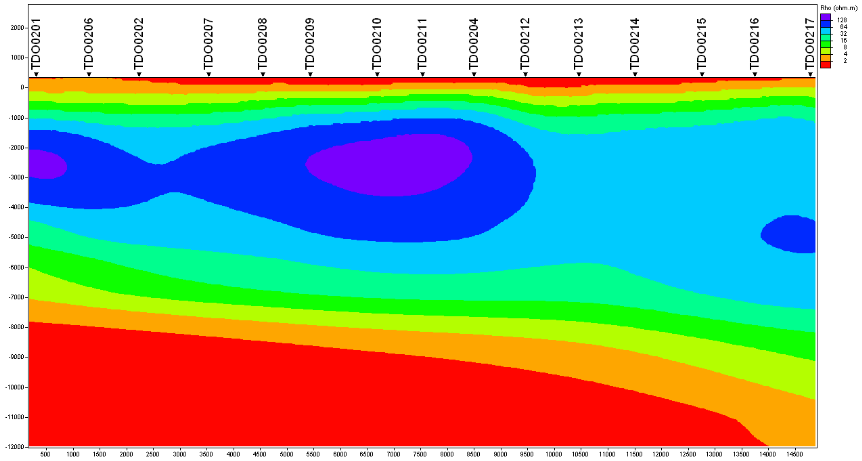

Figure 5. 2D MT cross section TDO02.

the geothermal system. The resistivity cross section also revealed possible fracture zones/faults in the Afar staratoid basalts (shown by vertical lines in Figure 4). This fracture zone may give rise to higher permeability and high temperature and presumably indicate upflow of geothermal fluids into the system.

2D MT cross section TDO02, (Figure 2 & 5), runs from Dubti Plain in the SW to Kurub volcanic complex in the NE with a total distance of about 15 km. The resistivity model shows a low resistivity thin surface layer, underlain by a high resistivity followed by low resistivity structure. The good conducting surface layer is thinner compared to that of TDO01. The good conducting structure at the bottom of the cross section is deeper compared to that of TDO01.

2D MT cross section TDO03, (Figure 2 & 6), runs from Dubti town in the SW to Gayale Plain in the NE with a total distance of about 17 km. The resistivity model TDO03 shows a low resistivity surface layer, underlain by a high resistivity followed by low resistivity structure to a depth of 10 km similar to TDO01. The resistivity cross section of TDO03 indicated presence of fracture zones/faults in the basalts (shown by vertical line in Figure 6).

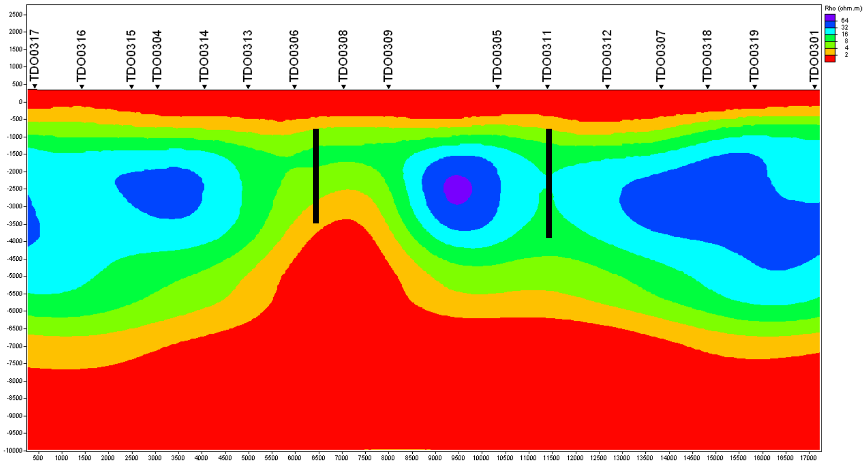

Figure 6. 2D MT cross section TDO03.

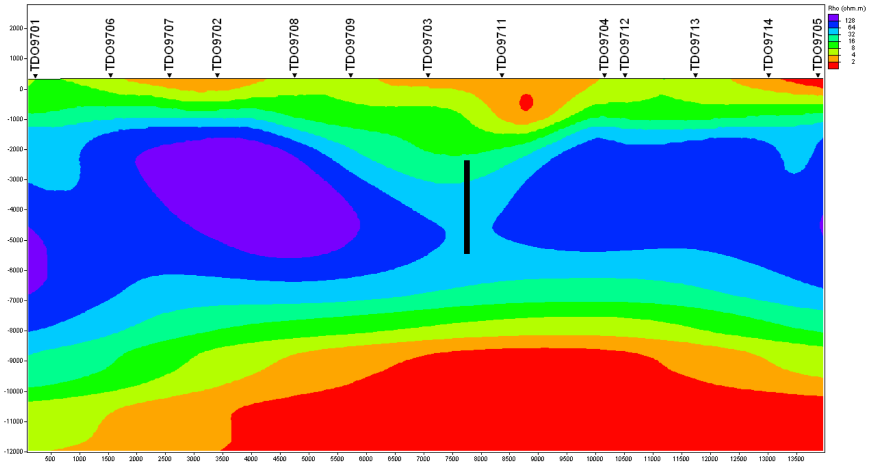

Figure 7. 2D MT cross section TDO97.

2D MT cross section TDO97, (Figure 2 & 7), runs from Gebelaytu ridge in SW to Seha plain in the NE. The 2D resistivity model TDO97 revealed low resistivity (≤ 8 Ωm) surface layer to a depth of about 500 m below sea level (b.s.l) (Figure 7). This low resistivity can be associated to sediments intercalated with afar stratoid series basalts. A high-resistivity anomaly, > 8Ωm, is observed from a depth of 500 m to about 9000 m b.s.l. This high resistivity is associated with Afar stratoid basalts. A low-resistivity anomaly, ≤ 8 Ωm, is observed from a depth of 9000 m to about 12000 m b.s.l. This conductive body can be interpreted as the heat source of the geothermal system. A possible fracture zone/fault is inferred from the resistivity cross section of TDO097 (shown by vertical line in Figure 7). This structure is interpreted as conduit through which geothermal fluids circulate.

The resistivity model resulting from 2D inversion is also presented as resistivity elevation slices at different elevations as shown on Figure 8(a-d). At an elevation of 1.2 km b.s.l, the 2D resistivity model elevation slice shows a high resistivity (> 16 Ωm) on broad regions of Dubti , Kurub plain and Ayrobera plain (Figure 8(a)). This broad high resistivity zone could be correlated to the Afar stratoid series basalts or chlorite-epidote alteration zone. At an elevation of 4 km b.s.l, the resistivity model shows a narrow low resistivity zone of ≤ 8 Ωm south east of the exploratory geothermal wells drilled in Dubti area (Figure 8(b)). The low resistivity structure could be associated with the upflow zone of the Tendaho geothermal system. The rest of the resistivity elevation slice is mostly characterized by high resistivity (> 16 Ωm). At an elevation of 6 km b.s.l., the narrow low resistivity zone observed at elevation of 4 km has broadened (which is located south east of the exploratory geothermal wells at Dubti area) (Figure 8(c)). At an

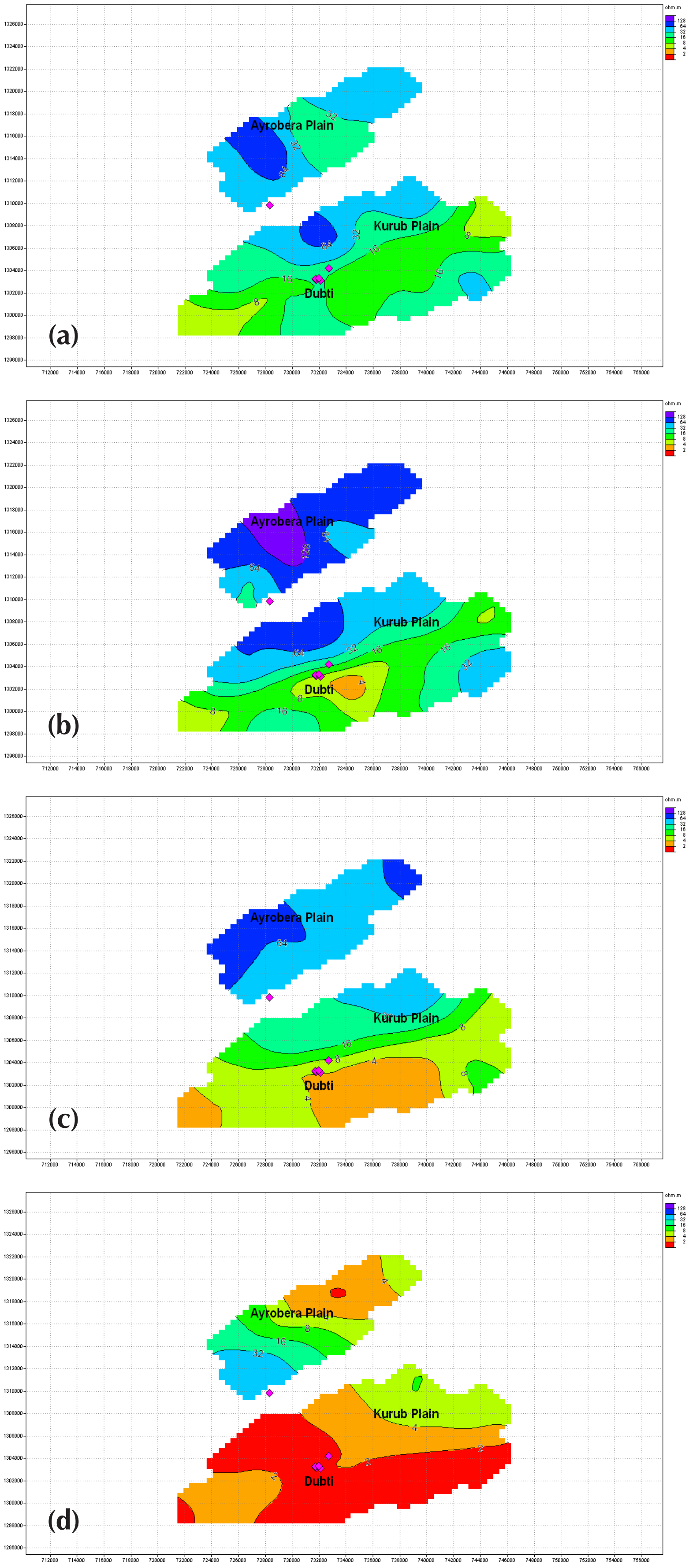

Figure 8. Resistivity elevation slices from 2D inversion at four elevations derived from inversion of the 84 MT sites: i.e. (a) at 1.2 km b.s.l; (b) at 4 km b.s.l ; (c) at 6 km b.s.l; and (d) at 9 km b.s.l. Purple diamonds = Geothermal wells; Black dots = MT sites.

elevation of 9 km b.s.l., the resistivity model shows a low resistivity (≤ 8 Ωm) on the entire region of Dubti, Kurub plain and North east sector of Ayrobera plain (Figure 8(d)). The south west sector of Ayrobera plain is characterized by high resistivity.

Conclusions

The 2D inversions of MT data on the seven profiles from Tendaho geothermal field revealed three main resistivity structures down to a depth of 10 km. The low resistivity surface layer can be interpreted as sediments, lateral flow of geothermal fluids or Zeolite-clay alteration zone (Aquater, 1996). Below the conductive layer, high resistivity (> 8 Ωm) is observed, which can be correlated to Afar stratoid basalts or epidote alteration zone as confirmed from alteration zones of well TD1, TD2 and TD3 (Aquater, 1996). The high resistivity structure can be associated with the deep reservoir of the geothermal system. The deep conducting layer is presumably associated with the heat source of the geothermal system.

The possible fracture zones in the basalts inferred from the 2D resistivity cross section on Profiles TDO01, TDO03 and TDO97 may give high temperature and high permeability.

The 2D resistivity elevation slices showed possible upflow zone south east of the exploratory wells drilled in Dubti area which is in agreement with the proposed upflow zone of Aquater (1996).

Acknowledgements

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